Hindawi
Discrete Dynamics in Nature and Society
Volume 2022, Article ID 7561841, 16 pages
https://doi.org/10.1155/2022/7561841

Research Article

Coordination of New Energy Vehicles Closed-Loop Supply Chain under Government Subsidies and Different Power Structures

Yuping Wu, Zhaoyang Tian, and Guilin Chang

Research Center of Energy Economics, School of Business Administration, Henan Polytechnic University, Jiaozuo 454003, China

Correspondence should be addressed to Guilin Chang; 1277164918@qq.com

Received 24 June 2022; Revised 16 August 2022; Accepted 26 October 2022; Published 3 November 2022

Academic Editor: Chun Wei

With the gradual retirement of the first batch of new energy vehicles in recent years, determining the optimal recycling mode has become an urgent concern. Considering the closed-loop supply chain, the government subsidy system, and different market power structures, this paper studies new energy vehicle recycling decisions and supply chain contract coordination. The results show that given an increase in government subsidies, the profit of the dominant agent in the closed-loop supply chain will be higher than that of the follower, and an increase in wholesale and recovery prices may lead to an increase in sales prices. In addition, the effect of government subsidies on battery recovery is better in cases of vehicle manufacturer dominance than in those of battery manufacturer dominance. Finally, when a battery manufacturer is in the dominant position, a revenue sharing contract can incentivize supply chain coordination; when a vehicle manufacturer is in the dominant position, a two-part tariff contract can realize coordination in the supply chain.

1. Introduction

The new energy vehicle recycling market in China has developed rapidly in recent years in response to the promotion of its "double carbon" goal. However, this development also presents new problems in the recycling market. At the 2021 EV 100 Forum, Bao Wei, the general manager of Zhejiang Huayou Recycling Technology Co., Ltd, suggested that the total recycling volume of battery recycling enterprises is less than 30% [1], which leads to a large number of used batteries flowing to informal recycling enterprises and makes it appear as if the market is "throwing good money after bad." In addition, with increasing competition in the market for new energy vehicles, the market structure has gradually changed, which has, on the one hand, created a conflict of interest between the members of its closed-loop supply chain and, on the other hand, weakened the effects of government subsidies and made it more difficult for the supply chain as a whole to achieve Pareto equilibrium. The disorganized state of the recycling market for retired new energy vehicles at present as well as the random dismantling of such vehicles make it very likely that the process will pollute the ground and water supply with heavy metals, thus harming people and the environment. Therefore, how to make government subsidy policy play a more significant role in the recycling of new energy vehicles and improve the efficiency of the supply chain deserves further exploration. Doing so will have a positive and important impact on enterprises in the supply chain and the supply chain as a whole such that they can obtain higher revenue, reduce the environmental pollution caused by discarded batteries, and enhance the overall advantage of the closed-loop supply chain market structure.

2. Literature Review

The existing research on closed-loop supply chains and their power structures has shown promising results. Scholars have focused their efforts on manufacturer-only dominance, retailer-only dominance, and the different power structures. The most noteworthy studies are on the pricing decisions of and contract coordination in closed-loop supply chains under different power structures. Pricing decisions. Xiao and Zhao [2] constructed a manufacturer-led, two-stage closed-loop supply chain and studied the influence of disassembly costs and recovery prices on the profit of decision-makers in the supply chain. Mondal et al. [3] outlined retailers' social responsibilities and discussed how their efforts affect the of supply chain members' optimal decision-making under one centralized decision model and three manufacturer-led decentralized models. Contract coordination. Luo and Li [4] constructed a dual-channel E-closed-loop supply chain with coexisting of online and offline channels, implemented a supply chain decision model that considered fairness concerns based on the manufacturer-dominant market and designed a scientific contract mechanism to present a decision-making short board for supply chains. Wang et al. [5] constructed a model of manufacturer-led centrality with and without fairness, in which manufacturers assume a certain degree of corporate social responsibility to pursue their own profit maximization. Ranjbar et al. [6] compared different power structures dominated by manufacturers and retailers, respectively, performed a comprehensive sensitivity analysis, considered its environmental and consumer welfare implications, and concluded that a retailer-led decentralization model tends to be the most efficient arrangement in closed-loop supply chains. Li et al. [7] studied emissions reduction and low-carbon publicity in closed-loop supply chains based on their power structure and introduced the Shapley value method and an incremental revenue sharing system. However, most of the above research focuses on the general closed-loop supply chain, and few studies specifically investigate that for new energy vehicles.

Because the government plays an important role in coordinating closed-loop supply chains, the study of the role of subsidy policy in shaping those supply chains has become widely discussed in the literature, particularly in terms of whether, how, and whom to subsidize. Li and Mu [8] constructed a decision-making model of a closed-loop battery supply chain with and without government regulation, respectively, and analyzed the optimal solution under both centralized and decentralized decision-making regimes and conducted a sample contract coordination for the upstream and downstream joint recycling of a three-stage closed-loop battery supply chain. Ma et al. [9] considered technology investment decisions and collaboration strategies between manufacturers and retailers and explored the impact of government regulations on supply chain members' decisions. Huang et al. [10] constructed a two-way dual-channel closed-loop supply chain for new energy vehicles, considered the optimal solution of each decision-making variable with and without government subsidies and conducted a comparative analysis from different perspectives. Yan and Xie et al. [11] combined the partial recovery and full recovery supply constraints to construct a two-cycle model that explores the pricing and coordination of battery production in the presence of government subsidies and the impact of those subsidies on the pricing of battery recovery and fracturing. Garai et al. [12] proposed a cost-effective government subsidy policy for growers and biofuels producers in the closed-loop herbs and medicinal plants supply chain by introducing a dual-objective closed-loop supply chain (CLSC) network.

The research on the closed-loop new energy vehicle supply chain is currently focused on battery recycling, ladder utilization, and production responsibility systems, in addition to considering government subsidies and market power structures. In terms of battery recycling and utilization, scholars focus on pricing decisions and contract coordination. Recycling pricing decisions. Gu et al. [13] studied a three-cycle closed-loop supply chain composed of battery manufacturers and remanufacturers and discussed the relationship among the yield rate, sorting rate, and recovery rate and its influence on supply chain decision-making. Lv [14] elaborated on the closed-loop supply chain recycling modes, pricing, recycling, and supply chain policies for new energy vehicles. According to the particularities of battery recycling, Zhong et al. [15] constructed a closed-loop battery supply chain system composed of manufacturers, sellers, and recyclers with respect to government subsidies, and compared and analyzed the optimal pricing, volumes, and revenues under five dominant modes. Supply chain contract coordination. Through combing, we found that the main contract types include revenue sharing, cost sharing, two-part pricing, and wholesale pricing, among which, revenue sharing is the most widely used. Zhu and Yu [16] proposed a remanufacturing revenue sharing model considering information sharing or not based on principal-agent theory to investigate the effect of screening contracts on the expected revenues of both parties. Yin and Liu [17] investigated the optimization effect of benefit-cost sharing contracts on model decisions based on carbon trading policies. Yao et al. [18] improved the effectiveness of cost-sharing and two-tariff pricing contracts in incentivizing retailers' corporate social responsibility (CSR) inputs and the effectiveness of closed-loop supply chain coordination based on CSR. He and Zhao [19] proposed a return policy for manufacturers and retailers to design a wholesale pricing contract that could result in a win-win situation for both parties.

The Extended Producer Responsibility (EPR) system is an important system in sustainable economic legislation, and China is gradually applying it to the new energy vehicle recycling market, while more developed Western countries already have a comparable system. Relatively few studies have considered the closed-loop new energy vehicle supply chain under the EPR system, particularly from the perspective of recycling strategies under the producer responsibility power structure. Bai and Liu [20] introduced two new concepts: the contribution of waste recycling to product sales and the contribution of design improvements to recycling profit and established the principal-agent contract model to consider manufacturers' incentives and retailers' inputs. Wang and Zhou [21] studied the Zen pricing model and obtained the optimal pricing strategy of each member of a closed-loop supply chain. Li et al. [22], based on the design problem of outsourcing recycling contracts under extended producer responsibility, established the optimal contract on the basis of incentive theory to minimize costs and meet the set constraints stipulated by

EPR. Sun et al. [23] proposed a complete closed-circuit recycling process for the management of used lithium-ion batteries in China from a producer responsibility perspective and considered such factors as grade utilization and resource recovery.

In sum, scholars have explored closed-loop supply chains from multiple perspectives and found that their pricing decisions and power structures have an important impact on the benefits of supply chain members, and government subsidies can help them reduce costs and increase their efficiency. Therefore, we intend to study the pricing, power structure, and government subsidies to further analyze decision-making in closed-loop new energy vehicle supply chains. The main contributions of this paper are as follows: first, large government subsidies and power structure are simultaneously introduced into the existing pricing research, which fills the gap in the related decision-making research. Second, we consider different power structures based on the producer responsibility system, and the relevant research is considered for cases in which the government only provides recycling subsidies for a single battery manufacturer. Third, revenue sharing and two-part tariff contracts are introduced to coordinate decisions under different power structures and provide theoretical support for the structural design of new energy vehicle recycling channels.

3. Hypotheses and Variables

In this paper, we consider a two-stage closed-loop supply chain system composed of a battery manufacturer and a vehicle manufacturer. In order to simplify the model and conform to the pricing decisions of the real closed-loop supply chain, the assumptions of this study are as follows:

Hypothesis 1. In the closed-loop supply chain system, both the battery and the vehicle manufacturer are risk-neutral, and both have sufficient supply capacity. In addition, the information among supply chain members is completely symmetrical.

Hypothesis 2. The subsidy object of the government is the battery manufacturer, and the subsidy for each recovered waste battery is s. The recycled waste battery can be used in remanufacturing, and the performance of the remanufactured product is the same as that of the new product, so there is no difference in pricing between the remanufactured product and the new product.

Hypothesis 3. The manufacturing cost of new batteries is higher than the remanufacturing cost of used batteries ($c_r < c_m$) [24]. The cost saved by the remanufacturing process is $0 \leq c_m - c_r = \Delta$. In order to ensure the profitability of battery manufacturers, we set $0 < A < \Delta$. That is, the cost saved through the remanufacturing process is no less than the recovery price.

Hypothesis 4. To facilitate comparison and analysis, we assume that the government subsidy intensity s, recovery price A , and effort cost coefficients k in all models are the same. Recovery effort cost is $1/2ke^2$ [25], where e is the battery recovery. This function shows that the cost of recycling efforts will rise rapidly as such efforts increase, which indicates that it is uneconomical to increase investment in recycling to improve the absolute level of product recycling.

Hypothesis 5. Referring to the literature [26, 27], demand is a linear function of price; that is, the demand function is: $q = a - bp$, where a is the market base sales volume ($a > 0$) and b is the price sensitivity.

Hypothesis 6. Referring to the literature [28], we assume a linear correlation between recovery rate and battery recovery, given by $\tau = \alpha e (0 < \tau < 1)$. This shows that improving battery recovery will increase the recovery rate. To simplify the calculation, the base recovery rate is assumed to be zero.

Hypothesis 7. For the convenience of calculation, the manufacturer's costs in the manufacturing and sales process are not considered. The parameters and their meanings are shown in Table 1.

4. Decision-Making Model for New Energy Vehicle Closed-Loop Supply Chains considering Power Structures and Government Subsidies

4.1. Centralized Decision-Making. In the case of an increase in government subsidies, the vehicle and the battery manufacturer make a unified decision, represented by the upper standard c in this model. In this scenario, the overall profit function of the supply chain is

$$\pi_T^c(e, p) = (a - bp)(p - c_m) + (a - bp)(s + \Delta - A)\alpha e - \frac{1}{2}ke^2. \quad (1)$$

We use backward induction to obtain the optimal sales price p^{c*}, the battery recovery e^{c*}, and the overall profitability of the supply chain π_T^{c*}.

4.2. Decision-Making Model for a Battery Manufacturer-Led Closed-Loop Supply Chain with Government Subsidies. In the decentralized decision-making case, each node enterprise in the supply chain aims to maximize its own interests. According to the principle of producer responsibility, the battery manufacturer is responsible for waste recycling. In this scenario, the battery manufacturer, as the battery supplier, plays a leading role in the supply chain. The upper standard BS represents the battery manufacturer-led model, and the profit function of the battery and the vehicle manufacturer are

Table 1: Variables and their meanings.

Variable symbol	Variable meaning
c_m	New battery production costs
c_r	Remanufacturing battery production costs
A	New energy vehicle recycling price
a	Market base sales
b	Price sensitivity coefficient
α	Recovery effort
k	Effort cost coefficient
s	Government subsidy rate
τ	Waste battery recovery $\tau = \alpha e\,(0 < \tau < 1)$
ω	New battery wholesale price
p	Vehicle manufacturer the sales price
Δ	Recycling batteries saves profits $\Delta = c - c_0$
e	Recovery effort
h	Profit sharing ratio
F	Transfer price
π_i^c	Profit function under centralized decision-making $(i = M, B, T)$
M	Vehicle manufacturer upper/lower bid
B	Battery manufacturer up/down
T	Overall profit subscript
π_i	Profit function of dominant rights under decentralized decision-making $(i = M, B, T)$
π_B^{iSS}	Profit function of battery manufacturers after contract under each power structure $(i = M, B, T)$
π_M^{BSS}	Profit function of vehicle manufacturers after contract under each power structure $(i = M, B, T)$
π_T^{MSS}	Overall profit function of the supply chain after contract under each power structure $(i = M, B, T)$

$$\pi_B^{BS} = (a - bp)(\omega - c_m) + (a - bp)(s + \Delta - A)\alpha e - \frac{1}{2}ke^2, \quad (2)$$

$$\pi_M^{BS} = (a - bp)(p - \omega). \quad (3)$$

We use backward induction to obtain the optimal sales price p^{BS*}, the battery recovery e^{BS*}, the wholesale price ω^{BS*}, the optimal sales volume q^{BS*}, the vehicle manufacturer profit π_M^{BS*}, the battery manufacturer profit π_B^{BS*}, and the overall profitability of the supply chain π_T^{BS*}.

4.3. Decision-Making Model for a Vehicle Manufacturer-Led Closed-Loop Supply Chain with Government Subsidies. In the increase in government subsidies, each nodal enterprise in the supply chain aims to maximize its own interests. In this scenario, the vehicle manufacturer is in the dominant position in the supply chain, where $p = \omega + m$, m is the expected per-unit revenue of the vehicle manufacturer, and the upper standard MS represents the battery manufacturer-led model. The profit function of the battery and vehicle manufacturer is the same as equations (2) and (3), respectively.

$$\pi_B^{MS}(\omega, e) = (a - bp)(\omega - c_m) + (a - bp)(s + \Delta - A)\alpha e - \frac{1}{2}ke^2, \quad (4)$$

$$\pi_M^{MS} = (a - bp)(p - \omega).$$

We use backward induction to obtain the optimal sales price p^{BS*}, the battery recovery e^{BS*}, the wholesale price ω^{BS*}, the optimal sales volume q^{BS*}, the vehicle manufacturer profit π_M^{BS*}, the battery manufacturer profit π_B^{BS*}, and the overall profitability of the supply chain π_T^{BS*}. The equilibrium solution under each decision-making scenario is shown in Table 2. The proof of the above is provided in Appendix A.

5. Contract Coordination with Government Subsidies

5.1. Decision-Making Model for a Battery Manufacturer-Led Closed-Loop Supply Chain with Government Subsidies. Battery manufacturers can introduce profit-sharing contracts to improve their own profits and those of the overall supply chain to a certain extent. In this scenario, battery manufacturers share a certain percentage of vehicle manufacturers' gross profits. Then, a new wholesale price is offered to the vehicle manufacturer to compensate for the shared profits, thus improving the profits of both parties as well as the overall profit. The details are as follows. Battery manufacturers first provide benefit-sharing contracts to vehicle manufacturers (ω, h). Then, the vehicle manufacturer determines the sales price. Finally, battery manufacturers determine their wholesale price and battery recycling effort.

The profit functions of the battery and the vehicle manufacturer are

$$\pi_B(\omega, e) = (a - bp)(\omega - c_m + (1 - h)p) + (a - bp)(s + \Delta - A)\alpha e - \frac{1}{2}ke^2, \quad (5)$$

$$\pi_M = (a - bp)(hp - \omega).$$

Table 2: Equilibrium solutions under each decision-making scenario.

Decision variable	Centralized decision-making	Battery manufacturer-led	Vehicle manufacturer-led
ω	dull	$2kbc_m + \eta a/\beta$	$2\eta c_m + \gamma(a - bc_m)/2\eta$
p	$kbc_m + \gamma a/\eta$	$\eta a + k(a + bc_m)/\beta$	$2\eta a - kb(a - bc_m)/2b\eta$
e	$b\alpha(s + \triangle - A)(a - bc_m)/\eta$	$b\alpha(s + \triangle - A)(a - bc_m)/\beta$	$b\alpha(s + \triangle - A)(a - bc_m)/2\eta$
q	$kb(a - bc_m)/\eta$	$kb(a - bc_m)/\beta$	$kb(a - bc_m)/2\eta$
π_M	dull	$k^2b(a - bc_m)^2/\beta^2$	$k(a - bc_m)^2/4\eta$
π_B	dull	$k\beta(a - bc_m)2/2\eta^2$	$k(a - bc_m)^2/8\eta$
π_T	$k(a - bc_m)^2/2\eta$	$k(2kb + \beta)(a - bc_m)2/2\beta^2$	$3k(a - bc_m)^2/8\eta$

$\eta = 2kb - b^2\alpha^2(s + \triangle - A), 2\beta = 4kb - b^2\alpha^2(s + \triangle - A), 2\gamma = kb - b^2\alpha^2(s + \triangle - A).2$

Under a benefit-sharing contract, when the wholesale price is $\omega_s^* = 2hkbc_m - hab\alpha^2(s + \Delta - A)^2/2kb - \alpha^2b^2(s + \Delta - A)^2$, the sales price is $p^{MSS*} = k(a + bc_m) - ab\alpha^2(s + \Delta - A)^2/2kb - \alpha^2b^2(s + \Delta - A)^2$, the battery recovery is $e^{MSS*} = b\alpha(s + \Delta - A)(a - bc_m)/2kb - \alpha^2b^2(s + \Delta - A)^2$, the total vehicle manufacturing profit is $\pi_{Ms}^* = hk^2b(a - bc_m)^2/[2kb - \alpha^2b^2(s + \Delta - A)^2]^2$, and the battery manufacturer's profit is $\pi_{Bs} = kb[2(1 - h)k - \alpha^2b(s + \Delta - A)^2](a - bc_m)^2/\ 2[2kb - \alpha^2b^2(s + \Delta - A)^2]^2$. In this case, the overall profitability of the supply chain is $\pi_T^{MS*} = k[2kb - \alpha^2b^2(s + \Delta - A)^2](a - bc_m)^2/2[2kb - \alpha^2b^2(s + \Delta - A)^2]^2$. When benefit sharing is achieved, $2k - \alpha^2b(s + \Delta - A)^2/[4k - b\alpha^2(s + \triangle - A)^2] \geq h \geq [2kb - \alpha^2b^2(s + \Delta - A)^2]^2/[4kb - b^2\alpha^2(s + \triangle - A)^2]^2$. To validate the contract, the manufacturer's optimal wholesale price should be the same as that under a centralized decision-making regime, and $\pi_{Bs} \geq \pi_B$, $\pi_{Ms} \geq \pi_M$.

5.2. Decision-Making Model for a Vehicle Manufacturer-Led Closed-Loop Supply Chain with Government Subsidies. In order to obtain maximum profits, vehicle manufacturers introduce two-part tariff contracts in supply chains in which they dominate. Under two-part tariff contracts, the vehicle manufacturer provides a certain amount of profit to the battery manufacturer to cover recovery costs, and then the battery manufacturer updates its wholesale price to account for the profit shared by the vehicle manufacturer. The details are as follows. Vehicle manufacturers offer a two-part tariff contract to battery manufacturers (ω, F). Then, battery manufacturers decide upon their wholesale price and battery recycling effort. Finally, the vehicle manufacturer determines the sales price. The profit function and related constraints for the vehicle manufacturer in this scenario are as follows:

$$\pi_M = (a - bp)(p - \omega) - F,$$
$$s.t.\begin{cases} \pi_B^{MSS} = (a - bp)(\omega - c_m) + (a - bp)(s + \Delta - A)\alpha e - \dfrac{1}{2}ke^2 + F \geq \pi_B^{MS*} \\ e = e^{c*} \\ \omega = c_m \end{cases}. \tag{6}$$

The first two constraint conditions are similar to the incentive compatibility constraint, and the last condition is the individual rationality constraint. After the contract is finalized, the profit of the battery manufacturer cannot be lower than the profit under the noncontract decentralization decision. According to the constraint conditions, $F = k[2kb - b^2\alpha^2(s + \triangle - A)^2]\ (a - bc_m)^2/8[2kb - b^2\alpha^2(s + \triangle - A)2]^2 - (a - bp)(\omega - c_m) - (a - bp)(s + \Delta - A)\alpha e + 1/2ke^2$ and substituting F into the manufacturer's profit function, we can obtain the following equation:

$$\pi_M^{MSS} = (a - bp)(p - c_m) - \frac{k\left[2kb - b^2\alpha^2(s + \triangle - A)^2\right](a - bc_m)^2}{8\left[2kb - b^2\alpha^2(s + \triangle - A)2\right]^2} + (a - bp)\frac{b\alpha^2(s + \triangle - A)^2(a - bc_m)}{2kb - \alpha^2b^2(s + \Delta - A)^2}$$
$$- \frac{1}{2}k\left[\frac{b\alpha(s + \Delta - A)(a - bc_m)}{2kb - \alpha^2b^2(s + \Delta - A)^2}\right]^2. \tag{7}$$

6. Results

We now compare the relevant variables before and after the revenue sharing contract is implemented.

Proposition 1. *In the case of an increase in government subsidies, an increase in unit recovery price A increases the sales price of new energy vehicles p and reduces their recovery rate τ and the overall profit π_T. Under an increase in government subsidies, the wholesale price of the battery is directly proportional to the sales price and inversely proportional to the recovery rate, regardless of whether the battery manufacturer or the vehicle manufacturer is dominant.*

Proposition 1 shows that, in the centralized decision-making scenario, increasing the unit recovery price will lead to a decrease in the overall profitability of the supply chain, so the enterprise will choose to increase the sales price, but that increase will in turn decrease demand, thus leading to a decrease in the recovery rate. When the battery manufacturer raises its wholesale price, the vehicle manufacturer increases the sales price to ensure its own profitability. If the recycling price of waste batteries remains unchanged, the increase of the wholesale price of the battery will reduce sales volume and reduce the recycling rate.

Proposition 2. *The sales price is positively correlated with the battery recovery cost coefficient. The wholesale price of batteries is directly proportional to the sales price of new energy vehicles and inversely proportional to the recovery rate of used batteries irrespective of whether the vehicle manufacturer or the battery manufacturer is dominant.*

Proposition 2 shows that vehicle manufacturers increase the sales price as the battery recovery cost coefficient increases, battery manufacturers increase their recycling effort to raise the battery scrap cost coefficient, and the recovery cost also increases. Therefore, rising battery wholesale prices will compensate for the loss caused by the increase in recycling costs, and vehicle manufacturers will protect their own interests by increasing the sales price. Under different power structures, vehicle manufacturers will increase the sales price to ensure their own profitability. As the price increases, the sales volume will decrease, thus reducing the recycling rate of used batteries.

Proposition 3. *(1) $\tau^{c*} > \tau^{MS*} > \tau^{BS*}$; (2) $\omega^{BS*} > \omega^{MS*}$. (3) $p^{c*} < p^{MS*} < p^{BS*}$; (4) $q^{c*} > q^{MS*} > q^{BS*}$, $q^{c*} = 2q^{MS*}$.*

According to the above-given formula, the recovery rate under centralized decision-making is greater than that under the increase in government subsidies and the recovery rate under the supply chain structure dominated by the vehicle manufacturer is greater than that under the battery manufacturer. Since ω^{c*} belongs to the overall internal transfer value of the supply chain in the increase in government subsidies it cannot be compared with the decentralized decision-making scenario. As can be seen from the above equation, the wholesale battery price under decentralized decision-making is lower than that under decentralized decision-making.

Proposition 3 shows that the incentive of battery manufacturers to recycle is fully mobilized under a centralized decision-making scenario, which increases battery sales, enhances the overall profitability of the supply chain, and reduces environmental pollution. When the battery manufacturer is in a dominant position in the supply chain, it has stronger bargaining power based on its own market advantage. When the vehicle manufacturer is in a dominant position, it has a strong incentive to reduce wholesale prices to advance its own interests, while the battery manufacturer, as a follower, is forced to accept lower wholesale prices.

Vehicle manufacturers can only offset the cost incurred by the increase in wholesale prices by increasing the sales price. Therefore, under the leadership of battery manufacturers, the sales price is $p^{c*} < p^{MS*} < p^{BS*}$. In addition, when the vehicle manufacturer is dominant, it has strong bargaining power, so the cost generated by the increase of the wholesale price will be transferred to the end consumer. The increase in profitability will attract more investors to enter the market, which will intensify the market competition and limit the cost transfer effect. Therefore, the sales price in the scenario led by the battery manufacturer is still higher than that led by the vehicle manufacturer. The increase in the sales price will reduce sales volume, so the sales volume in the scenario led by battery manufacturers is lower than that led by vehicle manufacturers.

Proposition 4. *(1) $\pi_T^{c*} > \pi_T^{BS*} > \pi_T^{MS*}$; (2) $\pi_M^{MS*} > \pi_M^{BS*}$; (3) $\pi_B^{BS*} > \pi_B^{MS*}$; (4) $\pi_M^{MS*} > \pi_B^{MS*}$; (5) $\pi_B^{BS*} > \pi_M^{BS*}$.*

Proposition 4 shows that by comparing the profits of supply chains under different power structures, we find that the profits of enterprises in a supply chain are positively correlated with their relative forces. Under the same power structure, the interests of the leading party are always higher than those of the followers, regardless of which party dominates. Therefore, the battle for market leadership between battery makers and vehicle manufacturers will be fierce given that both seek to maximize their own interests. Considering the production responsibility system, the waste recycling responsibilities shall be borne by the battery manufacturers, but as a result of vehicle manufacturers in the old battery recycling process demonstrating "free rider" behavior, the resulting benefits accrue to vehicle manufacturers and battery manufacturers do not have enough power to change this dynamic.

Proposition 5. $0 < \partial e^{BS*}/\partial s < \partial e^{MS*}/\partial s < \partial e^{C*}/\partial s$; $0 < \partial q^{BS*}/\partial s < \partial q^{MS*}/\partial s < \partial q^{C*}/\partial s$; $\partial p^{BS*}/\partial s < \partial p^{MS*}/\partial s < \partial p^{C*}/\partial s < 0$; $\partial \omega^{BS*}/\partial s < \partial \omega^{MS*}/\partial s < 0$.

Proposition 5 shows that when there is a government subsidy, both the recovery rate and sales volume are positively correlated with the government unit recovery subsidy. However, the increase in government subsidies varies by the power structure. Specifically, the recovery rate and sales volume are highest under centralized decision-making, and the range of changes with changes in government subsidies is also the largest, with the vehicle manufacturer-led the second-largest and the battery manufacturer-led the smallest. In fact, regardless of the dominance structure, the government subsidy is always subject to battery manufacturers improving the recycling rate, which they incentivized to do given its positive impact on their revenue. Moreover, with an increase in government subsidies for waste battery recycling, the recovery rate increases and vehicle manufacturers have more market power due to more transparent market information, Therefore, vehicle manufacturers can reduce the sales price to increase sales volume and maximize their profitability.

The sales and wholesale prices of new energy vehicles are negatively correlated with the level of government subsidies. Under different power structures, sales and wholesale prices decrease with increases in government subsidies to varying degrees. In the event of an increase in government subsidies, the government subsidy recovery efficiency is the highest and the range of changes in the government subsidy is also the largest; the vehicle manufacturer-led structure is next-highest, and the battery manufacturer-led structure is the lowest. The government unit recycling subsidy on battery wholesale prices is also important. Irrespective of the power structure, government subsidies for battery recycling can encourage battery recycling, and remanufacturing, recycling and government subsidies have played an important role in increasing battery manufacturers' profitability. When vehicle manufacturers are dominant, wholesale and retail prices fall, and the new energy industry as a whole becomes for profitable.

Proposition 6. *Under two-part tariffs,* $\tau^{c*} = \tau^{MSS*} > \tau^{MS*}$, $p^{c*} = p^{MSS*} < p^{MS*}$, $\pi_T^{c*} = \pi_T^{MSS*} > \pi_T^{MS*}$. *Under revenue sharing,* $\tau^{c*} = \tau^{BSS*} > \tau^{BS*}$, $p^{c*} = p^{BSS*} < p^{BS*}$, $\pi_T^{c*} = \pi_T^{BSS*} > \pi_T^{BS*}$.

The wholesale battery price is inversely proportional to the degree of profit sharing, and the profit functions of battery and vehicle manufacturers are positively correlated to it.

Proposition 6 shows that, in the case of vehicle manufacturer dominance, vehicle manufacturers can solve the double marginalization problem under decentralized decision-making by sharing part of the sales benefit with battery manufacturers, which improves the profitability of the supply chain. In the presence of coordination, retail prices are reduced and recycling is increased, which benefits consumers and promotes recycling. Both vehicle and battery manufacturers can obtain higher profits than they can under decentralized decision-making, and which party can obtain higher excess profits depends on the market leadership. In the case of battery manufacturer dominance, vehicle manufacturers can solve the double marginalization problem by sharing a certain proportion of sales with battery manufacturers.

The proof of the above is provided in Appendix B.

7. Numerical Analysis

To more directly reflect the trend of the variables used in this paper, this chapter uses MATLAB software to conduct empirical analyses and takes government subsidies as variables to analyze their influence on wholesale prices, retail prices, sales volume, battery recovery, level of recycling, and profit. According to the definitions of and relationships between the parameters and with reference to the research of Wang et al. [29], it is assumed that $a = 100$, $b = 4$, $c_m = 10$, $\Delta = 3$, $\alpha = 0.5$, $k = 50$, $A = 1$, $s \in (0, 5)$, and $h \in (0, 1)$. The change of each variable is shown in Figures 1–9.

From Figure 1, it can be seen that under different power structures, battery wholesale prices are negatively related to recycling subsidies, but battery manufacturers dominate when government subsidies are smaller, and battery wholesale prices are when battery manufacturers dominate. The three results are consistent with Proposition 1. Because battery manufacturers directly receive government subsidies, when they are in the leading position, the greater the government subsidies, the greater their bargaining power. This reduces vehicle manufacturers' "free rider" behavior, and when vehicle manufacturers are in a dominant position, they have more bargaining power and can lower wholesale prices through their own market advantage. Therefore, under the same conditions, the battery wholesale prices will always be lower than that in the case dominated by the battery manufacturer.

As can be seen from Figure 2, no matter the power structure, the government battery recovery subsidy is negatively correlated with the sales price of new energy vehicles, but the sales price decreases by different degrees under different power structures. The sales price of new energy vehicles decreases the most with an increase in government subsidies under centralized decisions. The sales price of new energy vehicles in the case of battery manufacturer dominance is lowest and that in the case of centralized decision-making is higher than that in the case of vehicle manufacturer dominance and higher than that in the case of battery manufacturer dominance, which is consistent with Proposition 4.

In centralized decision-making scenarios, enterprises to participate in information exchange and effectively avoid the "bullwhip effect," and thus government subsidies successfully transform the supply chain. When battery manufacturers lead, lowering prices is one of the most effective strategies. When vehicle manufacturers lead, they have greater bargaining power. Battery manufacturers reduce the wholesale price for small profits and quick sales, and vehicle manufacturers save on manufacturing costs and in turn reduce the sales price.

As can be seen from Figures 3 and 4, recycling effort and sales volume are positively correlated with government subsidies, and the trends are the same under the three decision-making modes, which are all higher than those of vehicle and battery manufacturers under centralized decision-making. The recycling effort and the level of recycling are the highest in the case of an increase in government subsidies, thus indicating that the recycling effort conversion rate is conducive to resource recycling. When decentralized decisions are made, the greater the government subsidy, the greater the battery recovery and the higher the recovery volume are. When battery manufacturers recycle, recycling volumes are higher under power structures dominated by vehicle manufacturers. The fact that recycling effort and volume grow faster with government subsidies under the vehicle manufacturer-led model indicates that recyclers are more active when battery manufacturers recycle. Under the guidance of vehicle manufacturers, battery manufacturers

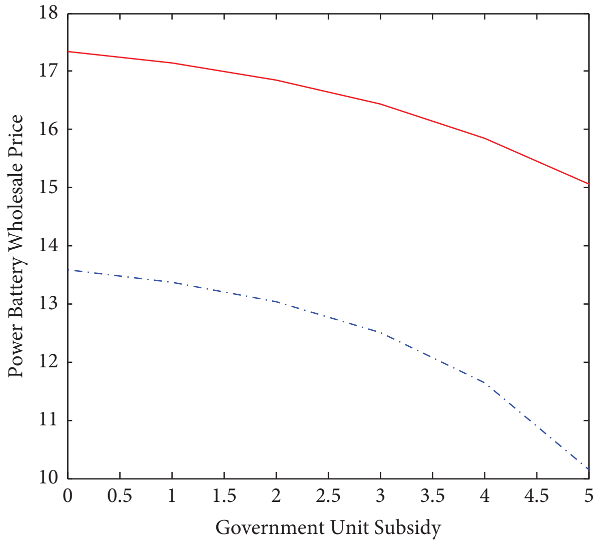

Figure 1: The influence of government subsidies on wholesale prices under different power structures.

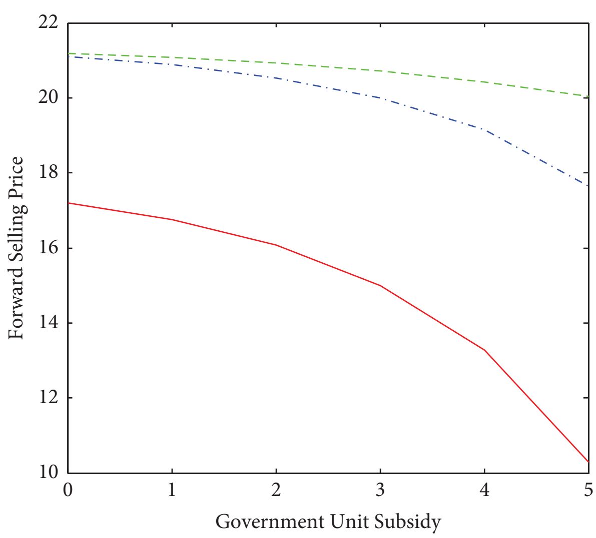

Figure 2: The influence of government subsidies on sales prices under different power structures.

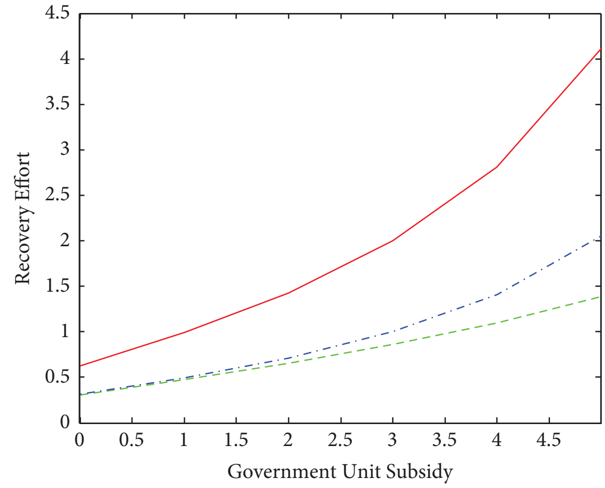

Figure 3: The influence of government subsidies on battery recovery under different power structures.

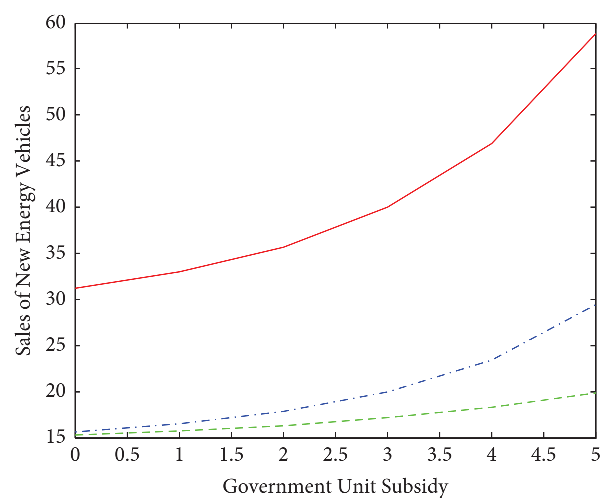

Figure 4: The influence of government subsidies on sales under different power structures.

mainly determine the wholesale price according to vehicle manufacturers' order quantities. Providing government subsidies to battery manufacturers strengthens the "free rider" psychology of vehicle manufacturers and reduces the sales price. When battery manufacturers are dominant, an increase in sales will indirectly lead to an increase in the remanufacturing profit of battery manufacturers, and a decrease in manufacturing cost will lead to a decrease in wholesale prices, while vehicle manufacturers also increase the demand by lowering the retail prices, which again verifies the conclusions in Figures 3 and 4.

As can be seen from Figures 5 and 6, the overall profitability of the supply chain under centralized decision-making is larger than that under the situations when vehicle and battery manufacturers dominate, and both are positively correlated with government subsidies. In the case of an increase in government subsidies, the total profit of each

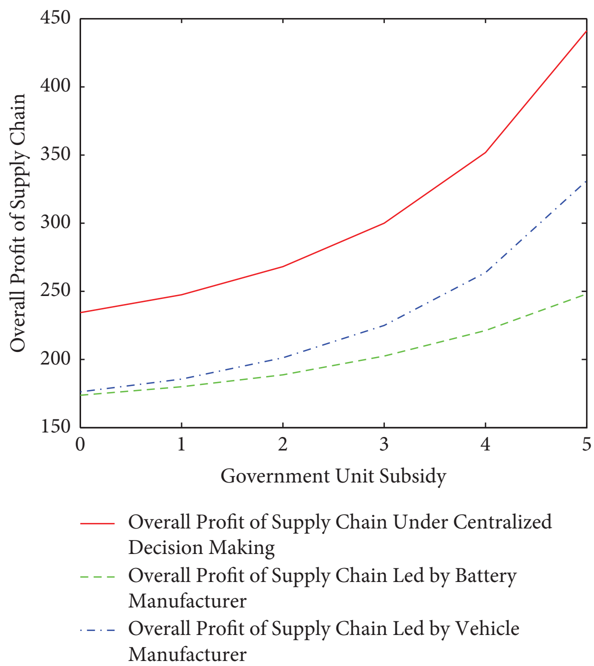

FIGURE 5: The influence of government subsidies on overall profits under different power structures.

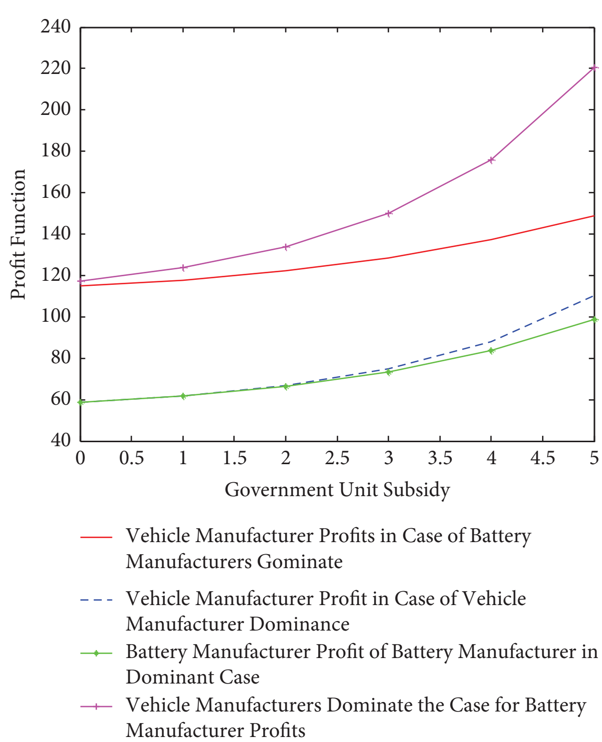

FIGURE 6: The influence of government subsidies on the profit of each subject under different power structures.

enterprise is higher than that of the battery manufacturer when under the control of the vehicle manufacturer. This indicates that vehicle manufacturers have more market power when they are in a dominant position, so their market

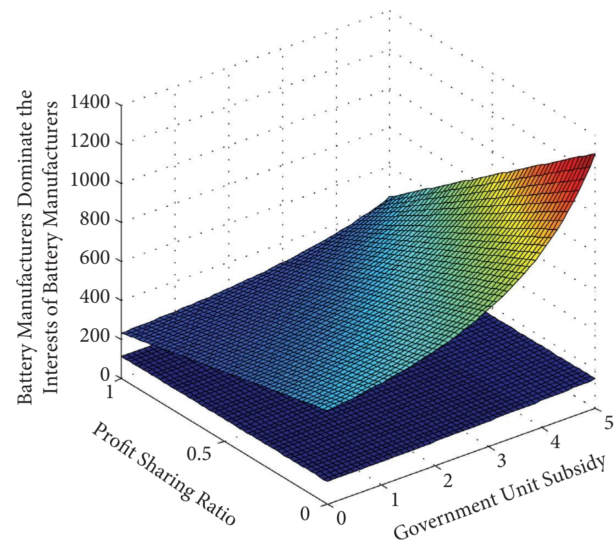

FIGURE 7: The impact of profit-sharing ratio and government unit subsidy on the interests of battery manufacturer-led battery manufacturers.

guidance is more conducive to increasing battery manufacturers' profits. When battery manufacturers fulfill their production responsibilities and actively recycle used batteries, vehicle manufacturers' profits grow faster under their own leadership and in the presence of government subsidies. The reason for this finding is that when vehicle manufacturers lead and battery manufacturer actively recover batteries, the battery manufacturer can adjust the wholesale price according to vehicle manufacturers' orders, thus increasing battery demand. When the battery manufacturer leads, it can preferentially set the wholesale price of the battery, thus guiding the vehicle manufacturer to set the sales price and increase demand. In addition, the profitability of the supply chain is the sum of the vehicle and battery manufacturers' profit, and when battery manufacturers recycle, vehicle manufacturers dominate; therefore, battery manufacturers recycle and vehicle manufacturers dominate.

As can be seen from Figures 7 and 8, in the case of battery manufacturer dominance, both the interests of the vehicle and the battery manufacturer under revenue sharing are higher than those without a revenue-sharing contract. When government subsidies remain unchanged, profits are positively correlated with the revenue sharing ratio. Given a higher percentage of revenue sharing, battery manufacturers and vehicle manufacturers increase more slowly, and the vehicle manufacturers is always greater than battery manufacturers. This is because when a higher percentage of benefit sharing, the reasons of large vehicle manufacturers need to separate interests. In addition, if the positive sales price is raised to ensure its own interests and the market sales volume is reduced, the manufacturer's interests will be reduced. Therefore, only when the proportion of interest sharing is moderate, the two parties will accept the contract. After the coordination of the two-part tariff contract, the interests of vehicle manufacturers are significantly improved and Pareto equilibrium is achieved, as shown in Figure 9.

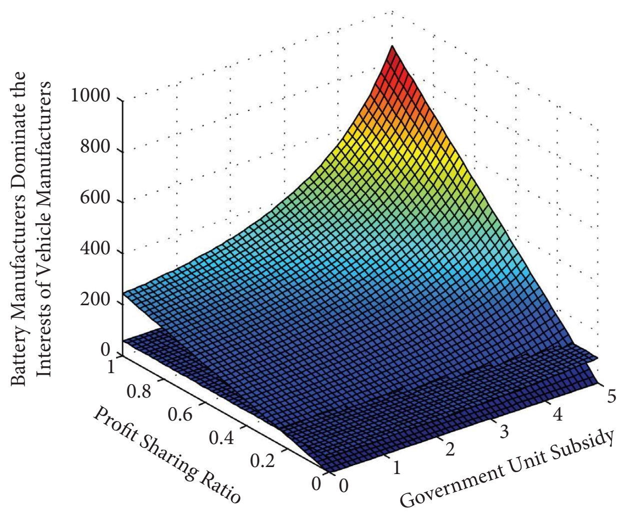

Figure 8: The influence of the profit-sharing ratio and government unit subsidy on the interests of battery manufacturers and vehicle manufacturers.

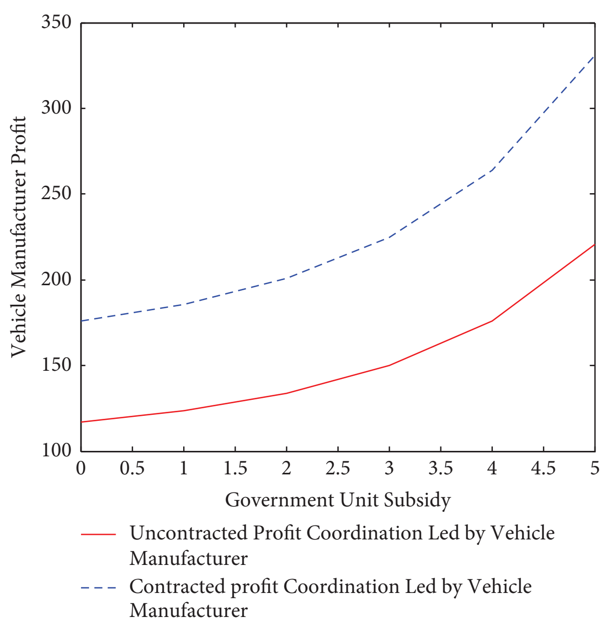

Figure 9: The influence of government subsidies before and after contract coordination on the profit of vehicle manufacturers when led by vehicle manufacturers.

Under the contract, the vehicle manufacturers improvement is more apparent. This is because the vehicle manufacturers are closer to consumers in the downstream of the market and is dominant in the market, so there will be more effective information and more powerful bargaining space. At this time the two sides have been affected more by government subsidies, so both sides will accept this contract when larger government subsidies, achieve Pareto optimality.

8. Conclusion and Discussion

8.1. Conclusion. This paper studies the influence of three power structures on closed-loop supply chain decisions considering battery manufacturer recycling and government subsidies. We conduct empirical tests to reveal the influence of government subsidies on the variables in and the profitability of the supply chain. The main conclusions are as follows:

(1) By comparing different power structures, it can be concluded that centralized decision-making is clearly better than increasing government subsidies. The price under centralized decision-making decreases fastest with an increase in government subsidies, and the demand for and level of recycling increase fastest in this scenario.

(2) The sales price of new energy vehicles varies with the dominant players in the supply chain, and the supply chain leaders can make sufficient profits by setting the optimal price based on their leadership position; with an increase in government subsidies, the level of government subsidies will affect product pricing and the profitability of the supply chain.

(3) When the government subsidy remains unchanged, the two-part tariff contract can realize supply chain coordination, and the recycling rate of waste batteries is always higher than that without the contract. Vehicle manufacturers are always willing to accept contract coordination; that is, whether it is a benefit-sharing or a two-part tariff contract, vehicle manufacturers can always make profits, while battery manufacturers are only willing to accept the contract when the proportions of revenue sharing and payment transfer are high.

8.2. Discussion. The paper constructs a model to analyze the decision-making and coordination strategies of the closed-loop new energy vehicle supply chain that considers government subsidies and power structures. It is believed that government subsidies can improve the profitability of the supply chain and the recycling rate of used batteries under different power structures by subsidizing recycling and incentivizing battery manufacturers to fulfill their production responsibilities.

(1) The government should weigh the advantages and disadvantages when formulating a recycling policy for new energy vehicles. Especially in the early stage of the development of the recycling market, it should encourage the relevant enterprises to recycle retired new energy vehicles. The government should adjust the intensity of subsidies according to market conditions to avoid creating a large financial burden. Government regulation policies should be formulated according to local conditions so that those with different intensities can have the same effect under different market power structures.

(2) The operational decisions of battery manufacturers are related to the development of the supply chain as a whole. Therefore, battery manufacturers should take the responsibility of recycling seriously and

establish a good internal recycling system. As vehicle manufacturers are closer to the consumers, and the government subsidies are more effective when they are in the leading position, vehicle manufacturers can raise consumers' awareness of social responsibility through advertising, and thus improve their own profitability.

(3) Regardless of the power structure of the supply chain, vehicle manufacturers and battery producers should proactively seek to cooperate through different contracts and take changes in recycling rates into account when making decisions to improve the overall efficiency of the supply chain.

This paper focuses on the coordination of pricing decisions in two-stage closed-loop supply chains under the influence of government subsidies under different power structures. The research process assumes that recycled new energy vehicles can be fully remanufactured and that the manufactured products are priced the same as new products. However, the real-world closed-loop supply chain pricing decision problem is far more complex than the model assumptions in this paper. It follows that differential pricing aspects of new energy vehicle products can be considered in future research. In addition, only profit-sharing and two-part pricing contracts are used to coordinate the supply chain, and other contracts may have an equally important impact on the coordination of closed-loop supply chains. Thus, the impact of other types of contracts on profits in the coordination process can be considered in future studies.

Appendix

A. Proof of Chapter

Proof. of Chapter 3.1. If the Hessian matrix is obtained by dividing equation (3.1) into two-system partial derivatives for each choice variable, we obtain the following equation:

$$H\pi_T^c = \begin{pmatrix} \frac{\partial^2 \pi_T^c}{\partial p^2} & \frac{\partial^2 \pi_T^c}{\partial p\, \partial e} \\ \frac{\partial^2 \pi_T^c}{\partial p\, \partial e} & \frac{\partial^2 \pi_T^c}{\partial e^2} \end{pmatrix} = \begin{pmatrix} -2b & -b\alpha(s+\Delta-A) \\ -b\alpha(s+\Delta-A) & -k \end{pmatrix}, \quad (A.1)$$

where the two conditions listed below are satisfied, the Hessian matrix is a negative definite, and equation (3.1) has a joint concavity for the selected variable in Table 2.

$$H_1 = -2b < 0, H_2 = 2bk - b^2\alpha^2(s+\Delta-A)^2 > 0. \quad (A.2)$$

□

Proof. of Chapter 3.2. Equations (3.2) and (3.3) are concave and have a joint concavity for the selected variable in Table 2 when the following conditions are satisfied: $\partial^2\pi_M^{BS}/\partial p^2 = -2b < 0$

$$H\pi_B = \begin{pmatrix} \frac{\partial^2 \pi_B^{BS}}{\partial \omega^2} & \frac{\partial^2 \pi_B^{BS}}{\partial \omega\, \partial e} \\ \frac{\partial^2 \pi_B^{BS}}{\partial \omega\, \partial e} & \frac{\partial^2 \pi_B^{BS}}{\partial e^2} \end{pmatrix} = \begin{pmatrix} -b & -\frac{b}{2}\alpha(s+\triangle-A) \\ -\frac{b}{2}\alpha(s+\triangle-A) & -k \end{pmatrix}, \quad (A.3)$$

where $H_1 = -b < 0$, $H_2 = kb - b^2/4\alpha^2(s+\triangle-A)^2 > 0$ □

Proof. of Chapter 3.3. Equations (3.4) and (3.5) are concave and have a joint concavity for the selected variable in Table 2 when the following conditions are satisfied:

$$H\pi_B = \begin{pmatrix} \frac{\partial^2 \pi_B^{MS}}{\partial \omega^2} & \frac{\partial^2 \pi_B^{MS}}{\partial \omega\, \partial e} \\ \frac{\partial^2 \pi_B^{MS}}{\partial \omega\, \partial e} & \frac{\partial^2 \pi_B^{MS}}{\partial e^2} \end{pmatrix} = \begin{pmatrix} -2b & -b\alpha(s+\triangle-A) \\ -b\alpha(s+\triangle-A) & -k \end{pmatrix}, \quad (A.4)$$

where $H_1 = -2b < 0$, $H_2 = 2bk - b^2\alpha^2 (s + \triangle - A) > 0$; $\partial^2 \pi_M^{MS}/\partial p^2 < 0$. □

B. Proof of Proposition

Proof of Proposition A.1. It is proved that the positive sales price, waste battery recovery rate, and overall profit of the supply chain take the partial derivative of the unit recovery price, respectively

:

$$\frac{\partial p_T^*}{\partial A} = \frac{2kb^2\alpha^2 (s + \Delta - A) \cdot (a - bc_m)}{\left[2kb - \alpha^2 b^2 (s + \Delta - A)^2\right]^2} > 0,$$
$$\frac{\partial \tau_T^*}{\partial A} = \frac{-b\alpha^2 (a - bc_m) \cdot \left[2kb + \alpha^2 b^2 (s + \Delta - A)^2\right]}{\left[2kb - \alpha^2 b^2 (s + \Delta - A)^2\right]^2} < 0, \quad (A.5)$$
$$\frac{\partial \pi_T^*}{\partial A} = \frac{-k\alpha^2 b^2 (s + \Delta - A)(a - bc_m)^2}{\left[2kb - \alpha^2 b^2 (s + \Delta - A)^2\right]^2} < 0.$$

The partial derivative of the wholesale price of the battery was obtained for the sales price and the recovery rate under the battery manufacturer and the vehicle manufacturer $\partial p^{BS}/\partial \omega^{BS} > 0$, $\partial p^{MS}/\partial \omega^{MS} > 0$, $\partial e^{BS}/\partial \omega^{BS} < 0$, $\partial e^{MS}/\partial \omega^{MS} < 0$. Since there is a linear relationship between the recovery effort and the recovery rate of used batteries, the wholesale price has the same trend. Proposition 1 is proved. □

Proof of Proposition A.2.

$$\frac{\partial p_T^*}{\partial k} = \frac{\alpha^2 b^2 (s + \Delta - A)^2 (a - bc_m)}{\left[2kb - \alpha^2 b^2 (s + \Delta - A)^2\right]^2} > 0. \quad (A.6)$$

The partial derivative of the selling price to wholesale price can be obtained under different power structures $\partial p_T^*/\partial \omega > 0$, The partial derivative of the recovery rate with respect to the wholesale price $\partial \tau_T^*/\partial \omega < 0$. Proposition 2 is proved. □

Proof of Proposition A.3.

$$\tau^{c*} - \tau^{MS*} = \frac{b\alpha^2 (s + \triangle - A)(a - bc_m)}{2\left[2kb - b^2\alpha^2 (s + \triangle - A)2\right]} > 0,$$
$$\tau^{MS*} - \tau^{BS*} = \frac{b\alpha^2 (s + \triangle - A)(a - bc_m)}{4kb - b^2\alpha^2 (s + \triangle - A)^2} > 0, \quad (A.7)$$
$$\omega^{MS*} - \omega^{BS*} = \frac{\left[\left[2k - b\alpha^2 (s + \triangle - A)^2\right]^2 + kb\alpha^2 (s + \triangle - A)^2\right](bc_m - a)}{2\left[2kb - b^2\alpha^2 (s + \triangle - A)2\right]\left[4kb - b^2\alpha^2 (s + \triangle - A)^2\right]} < 0.$$

$q^{MS*} - q^{BS*} = kb^3\alpha^2 \quad (s + \triangle - A)^2 (a - bc_m) \quad /2[2kb- b^2\alpha^2 \ (s + \triangle - A)^2][4kb - b^2 \alpha^2 (s + \triangle - A)^2] > 0$, $q^{c*} - q^{MS*} = kb(a - bc_m)/2[2kb - b^2\alpha^2 (s + \triangle - A)^2] > 0$, $p^{c*} - p^{MS*} = -k(a - bc_m)/2[2kb - b^2\alpha^2 (s + \triangle - A)2] < 0$, $p^{MS*} - p^{BS*} = -k \ b^2\alpha^2 (s + \triangle - A)^2 \ (a - bc_m)/2[2kb - b^2\alpha^2 \ (s + \triangle - A) 2][4kb - b^2\alpha^2 (s + \triangle - A)^2] < 0$Proposition 3 is proved. □

Proof of Proposition A.4.

$$\begin{aligned}
\pi_T^{c*} - \pi_T^{BS*} &= \frac{2k^3b^2(a-bc_m)^2}{\left[2kb-\alpha^2b^2(s+\Delta-A)^2\right]\left[4kb-\alpha^2b^2(s+\Delta-A)^2\right]^2} > 0,\\
\pi_T^{MS*} - \pi_T^{BS*} &= \frac{kb^2\alpha^2(s+\triangle-A)^2\left[b^2\alpha^2(s+\triangle-A)^2-8kb\right](a-bc_m)2}{8\left[2kb-\alpha^2b^2(s+\Delta-A)^2\right]\left[4kb-b^2\alpha^2(s+\triangle-A)^2\right]^2} < 0,\\
\pi_B^{BS*} - \pi_B^{MS*} &= \frac{k\left[4kb-3b^2\alpha^2(s+\triangle-A)^2\right](a-bc_m)2}{8\left[4kb-b^2\alpha^2(s+\triangle-A)^2\right]\left[2kb-b^2\alpha^2(s+\triangle-A)2\right]} > 0,\\
\pi_M^{BS*} - \pi_M^{MS*} &= \frac{-k\left[\left[2kb-b^2\alpha^2(s+\triangle-A)^2\right]^2+4k^2b^2\right](a-bc_m)^2}{4\left[2kb-b^2\alpha^2(s+\triangle-A)2\right]\left[4kb-b^2\alpha^2(s+\triangle-A)^2\right]^2} < 0,\\
\pi_M^{MS*} - \pi_B^{MS*} &= \frac{k\left[2kb-b^2\alpha^2(s+\triangle-A)^2\right](a-bc_m)^2}{8\left[2kb-b^2\alpha^2(s+\triangle-A)2\right]^2} > 0,\\
\pi_M^{BS*} - \pi_B^{BS*} &= \frac{-k\left[2kb-b^2\alpha^2(s+\triangle-A)^2\right](a-bc_m)2}{2\left[4kb-b^2\alpha^2(s+\triangle-A)^2\right]^2} < 0.
\end{aligned} \tag{A.8}$$

Proposition 4 is proved. □

Proof of Proposition A.5. In view of the optimal decision, the derivation and comparison of government unit subsidies can be obtained:

$$\begin{aligned}
\frac{\partial q^{C*}}{\partial s} &= \frac{2k\alpha^2b^3(s+\Delta-A)(a-bc_m)}{\left[2kb-\alpha^2b^2(s+\Delta-A)^2\right]^2} > 0,\\
\frac{\partial q^{MS*}}{\partial s} &= \frac{k\alpha^2b^3(s+\Delta-A)(a-bc_m)}{\left[2kb-\alpha^2b^2(s+\Delta-A)^2\right]^2} > 0,\\
\frac{\partial q^{BS*}}{\partial s} &= \frac{2k\alpha^2b^3(s+\Delta-A)(a-bc_m)}{\left[4kb-\alpha^2b^2(s+\Delta-A)^2\right]^2} > 0,\\
\frac{\partial q^{C*}}{\partial s} - \frac{\partial q^{MS*}}{\partial s} &= \frac{k\alpha^2b^3(s+\Delta-A)(a-bc_m)}{\left[2kb-\alpha^2b^2(s+\Delta-A)^2\right]^2} > 0,\\
\frac{\partial q^{BS*}}{\partial s} - \frac{\partial q^{MS*}}{\partial s} &= \frac{-k\alpha^2b^3(s+\Delta-A)(a-bc_m)\left[8k^2b^2-\left(\alpha^2b^2(s+\Delta-A)^2\right)^2\right]}{\left[4kb-\alpha^2b^2(s+\Delta-A)^2\right]^2\left[2kb-\alpha^2b^2(s+\Delta-A)^2\right]^2} < 0,\\
\frac{\partial e^{C*}}{\partial s} &= \frac{b\alpha(a-bc_m)\left[2kb+\alpha^2b^2(s+\Delta-A)^2\right]}{\left[2kb-\alpha^2b^2(s+\Delta-A)^2\right]^2} > 0,\\
\frac{\partial e^{MS*}}{\partial s} &= \frac{b\alpha(a-bc_m)\left[2kb+\alpha^2b^2(s+\Delta-A)^2\right]}{2\left[2kb-\alpha^2b^2(s+\Delta-A)^2\right]^2} > 0,\\
\frac{\partial e^{C*}}{\partial s} - \frac{\partial e^{MS*}}{\partial s} &= \frac{b\alpha(a-bc_m)\left[2kb+\alpha^2b^2(s+\Delta-A)^2\right]}{2\left[2kb-\alpha^2b^2(s+\Delta-A)^2\right]^2} > 0,\\
\frac{\partial e^{BS*}}{\partial s} &= \frac{b\alpha(a-bc_m)\left[4kb+\alpha^2b^2(s+\Delta-A)^2\right]}{\left[4kb-\alpha^2b^2(s+\Delta-A)^2\right]^2} > 0,\\
\frac{\partial e^{BS*}}{\partial s} - \frac{\partial e^{MS*}}{\partial s} &= \frac{-\alpha^3b^3(s+\Delta-A)^2\left(\left[4kb-\alpha^2b^2(s+\Delta-A)^2\right]\left[2kb-\alpha^2b^2(s+\Delta-A)^2\right]+2\left[8k^2b^2-\left(\alpha^2b^2(s+\Delta-A)^2\right)^2\right]\right)}{2\left[2kb-\alpha^2b^2(s+\Delta-A)^2\right]^2\left[4kb-\alpha^2b^2(s+\Delta-A)^2\right]^2} < 0.
\end{aligned} \tag{A.9}$$

The derivation and comparison of the subsidies of government units s for the more optimal decision can be obtained:

$$\begin{aligned}
\frac{\partial p^{C*}}{\partial s} &= \frac{2kb^2\alpha^2(s+\Delta-A)(bc_m-a)}{\left[2kb-\alpha^2b^2(s+\Delta-A)^2\right]^2}<0,\\
\frac{\partial p^{MS*}}{\partial s} &= \frac{kb^2\alpha^2(s+\Delta-A)(bc_m-a)}{\left[2kb-\alpha^2b^2(s+\Delta-A)^2\right]^2}<0,\\
\frac{\partial p^{BS*}}{\partial s} &= \frac{2kb^2\alpha^2(s+\Delta-A)(bc_m-a)}{\left[4kb-b^2\alpha^2(s+\triangle-A)^2\right]^2}<0,\\
\frac{\partial p^{BS*}}{\partial s}-\frac{\partial p^{MS*}}{\partial s} &= \frac{-kb^2\alpha^2(s+\Delta-A)(bc_m-a)\left(8k^2b^2-b^4\alpha^4(s+\triangle-A)^4\right)}{\left[4kb-b^2\alpha^2(s+\triangle-A)^2\right]^2\left[2kb-\alpha^2b^2(s+\Delta-A)^2\right]^2}<0,\\
\frac{\partial p^{C*}}{\partial s}-\frac{\partial p^{MS*}}{\partial s} &= \frac{kb^2\alpha^2(s+\Delta-A)(bc_m-a)}{\left[2kb-\alpha^2b^2(s+\Delta-A)^2\right]^2}<0,\\
\frac{\partial \omega^{BS*}}{\partial s} &= \frac{4k\alpha^2b^2(s+\Delta-A)(bc_m-a)}{\left[4kb-\alpha^2b^2(s+\Delta-A)^2\right]^2}<0,\\
\frac{\partial \omega^{BS*}}{\partial s}-\frac{\partial \omega^{MS*}}{\partial s} &= \frac{k\alpha^4b^4(s+\Delta-A)^3(bc_m-a)\left[4kb-3\alpha^2b^2(s+\Delta-A)^2\right]^2}{\left[4kb-\alpha^2b^2(s+\Delta-A)^2\right]^2\left[2kb-\alpha^2b^2(s+\Delta-A)^2\right]^2}<0.
\end{aligned} \tag{A.10}$$

Proposition 5 is proved. □

Proof of Proposition A.6.

$$\begin{aligned}
e^{c*}-e^{MSS*} &= \frac{b\alpha^2(s+\Delta-A)(a-bc_m)}{2kb-\alpha^2b^2(s+\Delta-A)^2}-\frac{b\alpha^2(s+\Delta-A)(a-bc_m)}{2kb-\alpha^2b^2(s+\Delta-A)^2}\\
\tau^{MSS*}-\tau^{BS*} &= \frac{2kb^2\alpha^2(s+\Delta-A)(a-bc_m)}{\left[2kb-\alpha^2b^2(s+\Delta-A)^2\right]\left[4kb-b^2\alpha^2(s+\triangle-A)^2\right]}>0,\\
p^{c*}-p^{c*} &= \frac{k(a+bc_m)-b\alpha^2(s+\Delta-A)^2}{2kb-\alpha^2b^2(s+\Delta-A)^2}-\frac{k(a+bc_m)-ab\alpha^2(s+\Delta-A)^2}{2kb-\alpha^2b^2(s+\Delta-A)^2}\\
p^{BSS*}-p^{BS*} &= \frac{-kb^2\alpha^2(s+\triangle-A)^2(a-bc_m)}{2\left[2kb-b^2\alpha^2(s+\triangle-A)2\right]\left[4kb-b^2\alpha^2(s+\triangle-A)^2\right]}<0.
\end{aligned} \tag{A.11}$$

$\pi_T^{c*}-\pi_T^{BSS*}=k\ [2kb-\alpha^2b^2(s+\Delta-A)^2](a-bc_m)^2/2\,[2kb-\alpha^2b^2\ (s+\Delta-A)^2]^2-k[2kb-\alpha^2b^2(s+\Delta-A)^2]\,(a-bc_m)^2/2[2kb\ -\alpha^2b^2(s+\Delta-A)^2]^2=0$, $\pi_T^{c*}-\pi_T^{BS*}=2k^3b^2(a-bc_m)^2/[2kb-\alpha^2b^2(s+\Delta-A)^2][4kb\ -\alpha^2b^2(s+\Delta-A)^2]^2>0$ The proportion of wholesale prices h can be derived from revenue sharing ω_s^*: $\partial\omega_s^*/\partial h=2kbc_m-ab\alpha^2(s+\Delta-A)^2/2kb-\alpha^2b^2(s+\Delta-A)^2<0$; The proportion of wholesale prices h can be derived from battery manufacturer and vehicle manufacturer can be obtained as follows: $\partial\pi_{Bs}^*/\partial h=-k^2b(a-bc_m)^2/[2kb-\alpha^2b^2(s+\Delta-A)^2]^2<0$, $\partial\pi_{Ms}^*/\partial h=k^2b(a-bc_m)^2/[2kb-\alpha^2b^2(s+\Delta-A)^2]^2>0$.

$$
\begin{aligned}
e^{c*}-e^{MSS*}&=\frac{b\alpha^2(s+\Delta-A)(a-bc_m)}{2kb-\alpha^2b^2(s+\Delta-\ A)^2}-\frac{b\alpha^2(s+\Delta-A)(a-bc_m)}{2kb-\alpha^2b^2(s+\Delta-\ A)^2}\\
\tau^{MSS*}-\tau^{MS*}&=\frac{2kb^2\alpha^2(s+\Delta-A)(a-bc_m)}{\left[2kb-\alpha^2b^2(s+\Delta-\ A)^2\right]\left[4kb-b^2\alpha^2(s+\triangle-\ A)^2\right]}>0,\\
p^{c*}-p^{MSS*}&=\frac{k(a+bc_m)-ab\alpha^2(s+\Delta-A)^2}{2kb-\alpha^2b^2(s+\Delta-\ A)^2}-\frac{k(a+bc_m)-ab\alpha^2(s+\Delta-A)^2}{2kb-\alpha^2b^2(s+\Delta-\ A)^2}\\
p^{MSS*}-p^{MS*}&=\frac{-kb^2\alpha^2(s+\triangle-A)^2(a-bc_m)}{2\left[2kb-b^2\alpha^2(s+\triangle-A)2\right]\left[4kb-b^2\alpha^2(s+\triangle-\ A)^2\right]}<0.
\end{aligned}
\tag{A.12}
$$

$\pi_T^{c*}-\pi_T^{MSS*}=k[2kb-\alpha^2b^2(s+\Delta-A)^2](a-bc_m)^2/2[2kb-\alpha^2b^2(s+\Delta-\ A)^2]^2-k[2kb-\alpha^2b^2(s+\Delta-A)^2](a-bc_m)^2/2[2kb-\alpha^2b^2(s+\Delta-A)^2]^2=0$, $\pi_T^{c*}-\pi_T^{MS*}=2k^3b^2(a-bc_m)^2/[2kb-\alpha^2b^2(s+\Delta-\ A)^2][4kb-\alpha^2b^2(s+\Delta-\ A)^2]^2>0$. Proposition 6 is proved. □

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The study was supported by (1) Major Project of Philosophical and Social Science in Henan Provincial Higher Education Institutions (Grant no. 2022-YYZD-07), (2) Major Project of Philosophical and Social Science in Henan Provincial Higher Education Institutions (Grant no. 2023-JCZD-15), and (3) Think Tank Research Project of Colleges and Universities in Henan Province (Grant no. 2023ZKYJ11).

References

[1] Z. Wang, “Where do “retired” EV batteries go?” *China Report*, vol. 5, pp. 76–78, 2021.

[2] M. Xiao and M. K. Zhao, “Research on the recovery channel of manufacturer-oriented two-stage closed- loop supply chain,” *Journal of Beijing Vocational College of Finance and Trade*, vol. 35, no. 3, pp. 35–40, 2019.

[3] C. Mondal, B. C. Giri, and S. Biswas, “Integrating Corporate Social Responsibility in a closed- loop supply chain under government subsidy and used products collection strategies,” *Flexible Services and Manufacturing Journal*, vol. 34, no. 1, pp. 65–100, 2021.

[4] Z. C. Y. Luo and F. Li, “A manufacturer-led Decision-making and coordination model for dual-channel E-closed-loop Supply Chain under equity concerns,” *Logistics technology*, vol. 44, no. 1, pp. 121–127, 2021.

[5] Y. Y. Wang, M. Su, L. Shen, and R. Y. Tang, “Decision-making of closed-loop supply chain under Corporate Social Responsibility and fairness concerns,” *Journal of Cleaner Production*, vol. 284, Article ID 125373, 2021.

[6] Y. Ranjbar, H. Sahebi, J. Ashayeri, and A. Teymouri, “A competitive dual recycling channel in a three-level closed loop supply chain under different power structures: pricing and collecting decisions,” *Journal of Cleaner Production*, vol. 272, Article ID 122623, 2020.

[7] H. Li, C. X. Wang, L. Xu, and W. Ou, “Decision-making and Coordination of carbon emission reduction and low carbon Publicity in closed-loop Supply chain,” *Computer Integrated Manufacturing Systems*, vol. 24, no. 5, pp. 1279–1291, 2018.

[8] X. Li and D. Mu, “Research on recovery pricing and coordination mechanism of power battery closed-loop supply chain,” *Soft Science*, vol. 32, no. 11, pp. 124–129, 2018.

[9] S. G. Ma, Y. He, R. Gu, and S. S. Li, “Sustainable supply chain management considering technology investments and government intervention,” *Transportation Research Part E: Logistics and Transportation Review*, vol. 149, Article ID 102290, 2021.

[10] H. Huang, X. Zhou, and J. Zhang, “Pricing of new energy vehicle bidirectional dual-channel closed-loop supply chain under government subsidy,” *Systems Engineering*, vol. 38, no. 4, pp. 69–77, 2020.

[11] J. Yan and Z. Xie, “A pricing model of power battery closed-loop supply chain under government subsidies,” *IOP Conference Series: Earth and Environmental Science*, vol. 546, no. 2, Article ID 022044, 2020.

[12] A. Garai, S. Chowdhury, B. Sarkar, and T. K. Roy, “Cost-effective subsidy policy for growers and biofuels-plants in closed-loop supply chain of herbs and herbal medicines: an interactive bi-objective optimization in T-environment,” *Applied Soft Computing*, vol. 100, Article ID 106949, 2021.

[13] X. Y. Gu, P. Ieromonachou, L. Zhou, and M. L. Tseng, “Developing pricing strategy to optimise total profits in an electric vehicle battery closed loop supply chain,” *Journal of Cleaner Production*, vol. 203, pp. 376–385, 2018.

[14] C. X. Lv, “Research on pricing coordination of closed-loop supply chain for power battery recycling, ” management and technology of small and medium-sized enterprises (the next ten days),” vol. 11, pp. 75-76, 2020.

[15] D. S. Zhong, N. Sun, and S. R. Sun, “Research on power battery closed-loop supply chain under multiple dominant modes,” *Practice and Understanding of Mathematics*, vol. 50, no. 13, pp. 68–80, 2020.

[16] X. D. Zhu and L. F. Yu, “Screening contract excitation models involving closed-loop supply chains under asymmetric

information games: a case study with new energy vehicle power battery," *Applied Sciences-Basel*, vol. 91461 pages, 2019.

[17] Y. Yin and F. C. Liu, "Carbon emission reduction and coordination strategies for new energy vehicle closed-loop supply chain under the carbon trading policy," *Complexity*, vol. 2021, pp. 1–17, Article ID 3720373, 2021.

[18] F. M. Yao, Y. L. Yan, and C. X. Teng, "Operation coordination of closed-loop supply chain considering government subsidies and CSR input," *Journal of Systems Engineering*, vol. 36, no. 06, pp. 817–832, 2021.

[19] Y. He and X. Zhao, "Coordination in multi-echelon supply chain under supply and demand uncertainty," *International Journal of Production Economics*, vol. 139, no. 1, pp. 106–115, 2012.

[20] S. Bai and H. Liu, "Research on coordination mechanism of closed-loop supply chain based on EPR system," *Management Review*, vol. 23, no. 12, pp. 156–165, 2011.

[21] X. F. Wang and Y. X. Zhou, "Research on pricing Model of waste Household appliances closed-loop Supply Chain based on EPR," *Logistics Engineering and Management*, vol. 35, no. 8, pp. 65–67, 2013.

[22] X. Li, Y. Li, and K. Govindan, "An incentive model for closed-loop supply chain under the EPR law," *Journal of the Operational Research Society*, vol. 65, no. 1, pp. 88–96, 2014.

[23] S. Q. Sun, C. X. Jin, W. Z. He, G. M. Li, H. C. Zhu, and J. W. Huang, "Management status of waste lithium-ion batteries in China and a complete closed-circuit recycling process," *Science of the Total Environment*, vol. 776, Article ID 145913, 2021.

[24] W. B. Wang, J. F. Ding, Z. H. Wang, and Q. L. Da, "Research on government reward and punishment mechanism of retailer-led closed-loop supply chain from the perspective of responsibility sharing," *Chinese Management Science*, vol. 27, no. 7, pp. 127–136, 2019.

[25] C. Zhang and Y. X. Chen, "Decision and coordination of cascade utilization power battery closed-loop supply chain with economies of scale under government subsidies," *Operations Research and Management Science*, vol. 30, no. 12, pp. 72–77+91, 2021.

[26] S. Z. Bai and X. L. Zhang, "Research on pricing of double Recovery channel closed-loop Supply Chain based on different subsidy Modes," *Ecological Economy*, vol. 36, no. 7, pp. 95–104, 2020.

[27] W. M. Di, W. Q. Xu, and X. Q. Xia, "Government subsidy Strategy and Effect analysis of closed-loop Supply Chain based on dealer remanufacturing," *Operations Research and Management*, vol. 30, no. 2, pp. 102–109, 2021.

[28] Z. J. Zhang, M. J. Guo, and Q. P. Chen, "Pricing strategy and coordination mechanism of power battery gradient utilization in closed-loop supply chain under EPR," *Industrial Engineering*, vol. 23, no. 3, pp. 10–18, 2020.

[29] J. G. Wang, L. Z. Dong, and J. H. Chang, "Pricing decision of closed - loop supply chain under government subsidies," *Science and Management*, vol. 40, no. 3, pp. 50–57, 2020.